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SUBJECT: FIFTH MONTHLY PROGRESS REPORT ("[illegible] HEAT TRANSFER FOR CRYOGENICS"), NAS8-[illegible], FOR MONTH [illegible] OCTOBER 1963

PROGRESS: (During 5th report period)

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SUMMARY

During the fifth monthly report period, two new references were added bringing the total to 69. Calculations of the pool boiling minimum heat flux were carried out for hydrogen, nitrogen and oxygen. The theories for pool (natural convection) stable film boiling were reviewed. Work continued on the compilation of vapor physical properties for superheated conditions.

Literature Search and Classification of Data

Two new references were added and copies of two previously listed references were received and classified. No replies were received from the letters written to various authors requesting tabulated data. To date the following summarizes the status of the literature search and classification:

Number of references listed -	69	
Reference copies not yet received -	1	(No. 88)
References classified -	68	

Theory

Calculations were carried out for the pool film boiling minimum heat flux for hydrogen, nitrogen and oxygen using the six equations presented in the fourth monthly report for boiling above a horizontal plate. A typical plot for nitrogen is given in Figure 1 where $(q/A)_{min} \rho_V/(\rho_V)_f$ is plotted versus pressure up to about 75 per cent of the critical pressure. Experimental data for the pool film boiling minimum heat flux are very meager. A value from the rather detailed study of Flynn, et al (Ref. 63) for nitrogen boiling outside a horizontal tube is included in Figure 1. Although this represents a different geometrical configuration, relatively good agreement is obtained with the most recent Zuber equation.

A review of the available theories for pool (natural convection) stable film boiling of saturated liquids was completed. This boiling

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regime is much more amenable to theoretical development than pool nucleate boiling. Since the original theoretical derivations by L. A. Bromley in 1948 (Refs. 3 and 4), based on the similarity to condensation, a great deal of effort has been expended on improving the theory and extending it to different boiling surface geometries. The theories are best summarized with respect to the geometrical configuration. Corrections for the effect of thermal radiation through the vapor film may be important and are discussed at the end of this section.

<u>Long Horizontal Cylinders</u>. Bromley's original equation was:

$$h_c = C_1 \left[\frac{k_v^3 \; \rho_v \; (\rho_L - \rho_v) \; g \; \lambda'}{D \; (T_w - T_s) \; \mu_v} \right]^{1/4} \qquad (1)$$

where: The constant C_1 was found to be bracketed theoretically from 0.512 (stagnant liquid surrounding the tube to 0.724 (liquid moves completely freely with the vapor). An average experimental value of $C_1 = 0.62$ was determined by Bromley from experimental data.

and:

$$\lambda' = \lambda + 0.5 \, (c_p)_v \, (T_w - T_s) \qquad (2)$$

and all vapor properties are evaluated at:

$$T_{ave} = \frac{T_w + T_s}{2}$$

Bromley later (Ref. 97) modified Equation 2 to:

$$\lambda' = \lambda \left[1 + 0.4 \; \frac{(c_p)_v \; (T_w - T_s)}{\lambda} \right]^2 \qquad (3)$$

Rohsenow (Ref. 98) further modified Equation 3 to:

$$\lambda' = \lambda \left[1 + 0.675 \frac{(c_p)_v (T_w - T_s)}{\lambda} \right] \approx \lambda \left[1 + 0.34 \frac{(c_p)_v (T_w - T_s)}{\lambda} \right]^2 \quad (4)$$

More recently, McFadden and Grosh (Ref. 100) considered the effect of variable specific heat and Frederking (Ref. 104) presented a boundary layer analysis which accounted for interface momentum transport.

An alternate form of Equation 1 in terms of dimensionless groups as discussed by Frederking (Ref. 99) is:

$$Nu_D = 0.62 \left[Ra_D \left(\frac{\lambda'}{(c_p)_v (T_w - T_s)} \right) \right]^{1/4} \quad (5)$$

where:

$$Nu_D = \text{Nusselt number} = \frac{h_c D}{k_v} \quad (6)$$

$$Ra_D = \text{Rayleigh number} = \frac{g D^3 \rho_v (\rho_L - \rho_v) (c_p)_v}{k_v \mu_v} \quad (7)$$

In general, Equations 1 and 5 are accurate only for a restricted range of cylinder diameter. For very small diameters, the vapor film thickness may approach the diameter (this is not allowed for in the theory). For very large diameters, an h_c of zero is predicted which is not consistent with experimental findings. Modifications for the effect of diameter over a wide range are discussed by Banchero, et al (Refs. 1 and 2) and Frederking (Ref. 17) in the light of experimental data for horizontal wires and large cylinders.

Horizontal Plates (facing up). Based on a wave theory for natural convection, Chang (Ref. 101) developed the following equation which is rearranged in terms of the Rayleigh number:

$$Nu_{L_c} = 0.278 \left[Ra_{L_c} \left(\frac{\lambda}{(c_p)_v (T_w - T_s)} \right) \right]^{1/3} \quad (8)$$

where: L_c is substituted for D in Equations 6 and 7.

It should be noted that the characteristic length, L_c, in Equation 8 cancels out.

More recently, Berenson (Ref. 102) utilized the Taylor instability concept to derive the following equation in terms of the Rayleigh number for the region of the minimum:

$$Nu_B = 0.425 \left[Ra_B \left(\frac{\lambda'}{(c_p)_v (T_w - T_s)} \right) \right]^{1/4} \qquad (9)$$

where:

$$B = \left[\frac{g_c \sigma}{g(\rho_L - \rho_v)} \right]^{1/2}$$ is substituted for D in Equations 6 and 7.

Vertical Surfaces. Bromley (Refs. 3 and 4) also derived an expression for film boiling from a vertical surface assuming laminar flow. In terms of the average Nusselt number over a vertical length L and the Rayleigh number, his expression was:

$$Nu_L = C_2 \left[Ra_L \left(\frac{\lambda'}{(c_p)_v (T_w - T_s)} \right) \right]^{1/4} \qquad (10)$$

where:

L is substituted for D in Equations 6 and 7.

The constant C_2 in Equation 10 was theoretically determined by Hsu and Westwater (Ref. 26) to be bracketed between 0.667 and 0.943. Bonilla (Ref. 103) suggested an average value of 0.80.

Ellion (Ref. 105) derived an equation similar to Equation (10) for the case of uniform heat flux. He obtained a constant, C_2, of 0.716. More recently, a number of laminar boundary layer solutions have been developed including those of McFadden and Grosh (Ref. 100), Cess (Ref. 107), Sparrow and Cess (Ref. 108), Koh (Ref. 109), Koh and Nilson (Ref. 106) and Frederking (Ref. 104). The aim of these more rigorous analyses has been to account for inertia forces, convective energy transport, interfacial velocity, variable physical properties and interacting radiation and convection effects.

In many practical situations, the above laminar flow analyses for vertical surfaces become invalid. Hsu and Westwater (Ref. 110) observed heat fluxes 100 to 300 per cent greater than predicted by Equation 10. The increase was caused by the development of turbulent flow above a critical height corresponding to a critical vapor film thickness and film thickness Reynolds number. They developed an equation which accounted for the turbulent flow effects. Bankoff in a written discussion to Ref. 110 presented an alternate turbulent flow model.

Radiation Effects. In his original derivation for a horizontal cylinder, Bromley (Refs. 3 and 4) also included an expression for the transfer of heat from the cylinder wall, through the vapor, to the liquid by thermal radiation. He noted that the coefficient for convection, h_c, was dependent on the effective coefficient for radiation, h_r. For $h_r < h_c$, he developed the following approximate relations:

$$h_{total} = h_c + (3/4) h_r \qquad (11)$$

where:

$$h_r = \frac{\sigma' \; (T_w^4 - T_s^4)}{\left(\frac{1}{\epsilon_w} + \frac{1}{\alpha_L} - 1\right)(T_w - T_s)} \qquad (12)$$

In the case of N_2 boiling on a 0.350-inch horizontal carbon tube at atmospheric pressure, he found that the radiation contribution became important above a wall temperature of about 500°F. More recent evaluations of the effect of thermal radiation on film boiling have been presented by Chang (Ref. 101) and Koh and Nilson (Ref. 106).

Physical Properties of Superheated Vapor

Work was continued on compilation of the physical properties of superheated vapor from the melting point temperature to 3000°R and pressures to the critical.

Figures 2 and 3 present the density and specific heat of parahydrogen as a function of temperature and pressure. The thermal conductivity and viscosity are presently being tabulated using the method of corresponding states.

A report by Stewart, et al (Ref. 111) recently published by NBS gives density and enthalpy of oxygen from 100 to 540°R and pressures to 4500° psia. Specific heat will be computed from the enthalpy values. At the higher temperatures, density and specific heat will be computed by existing computer programs.

The computer programs for density and specific heat of nitrogen have been obtained, but values have not yet been tabulated.

Preliminary Recommendations

On the basis of the studies conducted during the first five months of this program, the following preliminary recommendations are made for a future program:

1. Experimental data for the boiling of oxygen under forced flow conditions are practically non-existent and should be obtained over a wide range of conditions.

2. Experimental data and theoretical analyses for cryogenic boiling under forced flow conditions with appreciable net vaporization are inadequate and a comprehensive study of this region should be carried out.

PLANS (for 6th report period)

During the sixth monthly report period, compilation and tabulation of experimental data points will continue. Theories for forced convection boiling under net vaporization conditions will be reviewed. Compilation of superheated vapor properties will be completed.

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NOMENCLATURE

c_p	Specific heat
D	Diameter
g	Acceleration due to gravity
g_c	Constant = 32.17 lbm-ft/lbf-sec^2
h_c	Convection heat transfer coefficient
h_r	Radiation heat transfer coefficient
k	Thermal conductivity
L_c	Characteristic length
T_s	Saturation temperature
T_w	Wall temperature
α_L	Absorptivity of liquid
ϵ_w	Emissivity of wall
λ	Latent heat of vaporization
ρ	Density
σ	Surface tension
σ'	Stefan-Boltzmann constant for radiation

Subscripts

L	Liquid
v	Vapor

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N_2: A4-B1-C5-D1-E1
N_2: A4-B1-C7-D1-E1
O_2: A1-B1-C5-D1-E2
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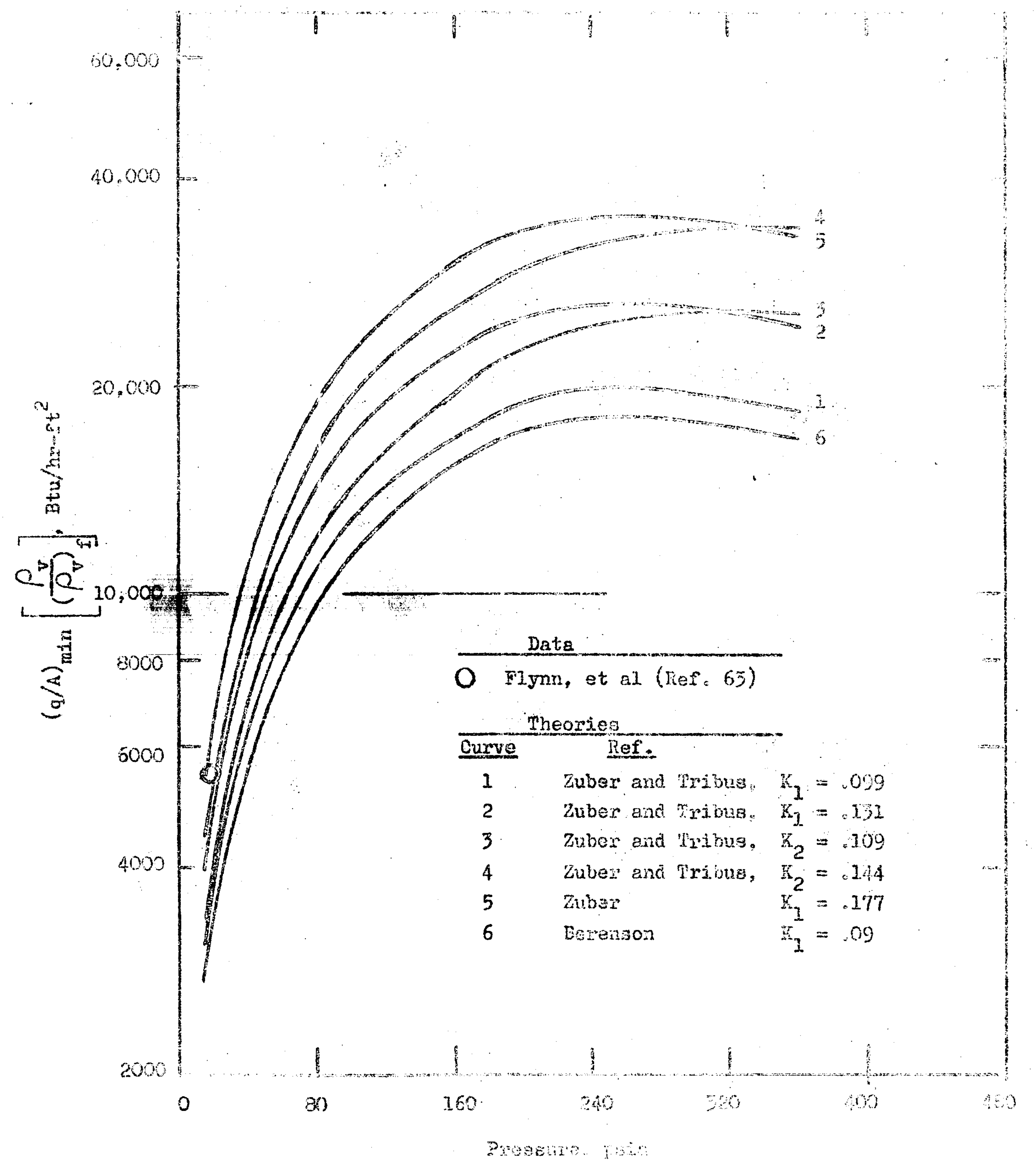

FIGURE 1 POOL BOILING MINIMUM HEAT FLUX FOR NITROGEN

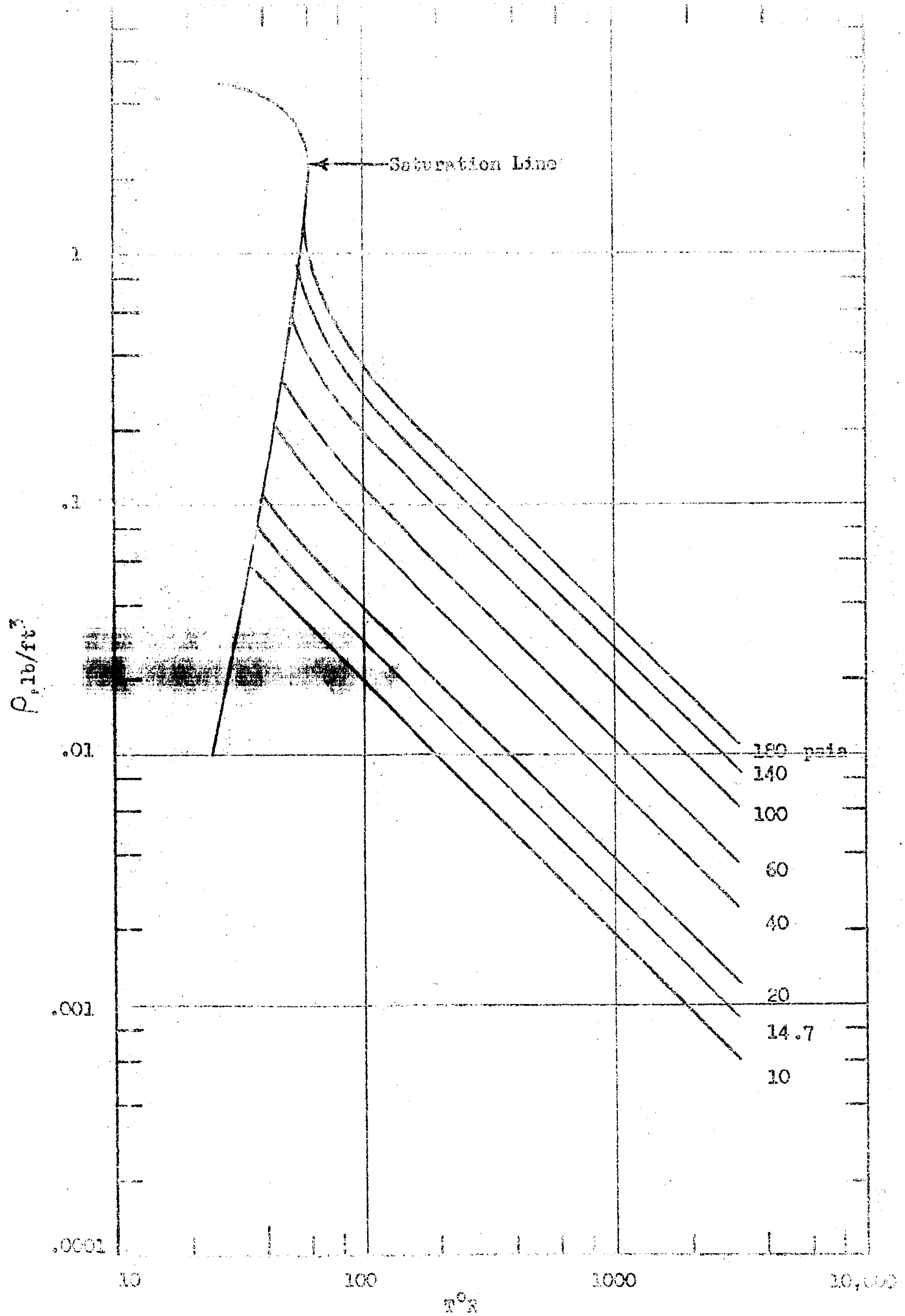

FIGURE 2 DENSITY OF PARA-HYDROGEN AS A FUNCTION OF TEMPERATURE AND PRESSURE

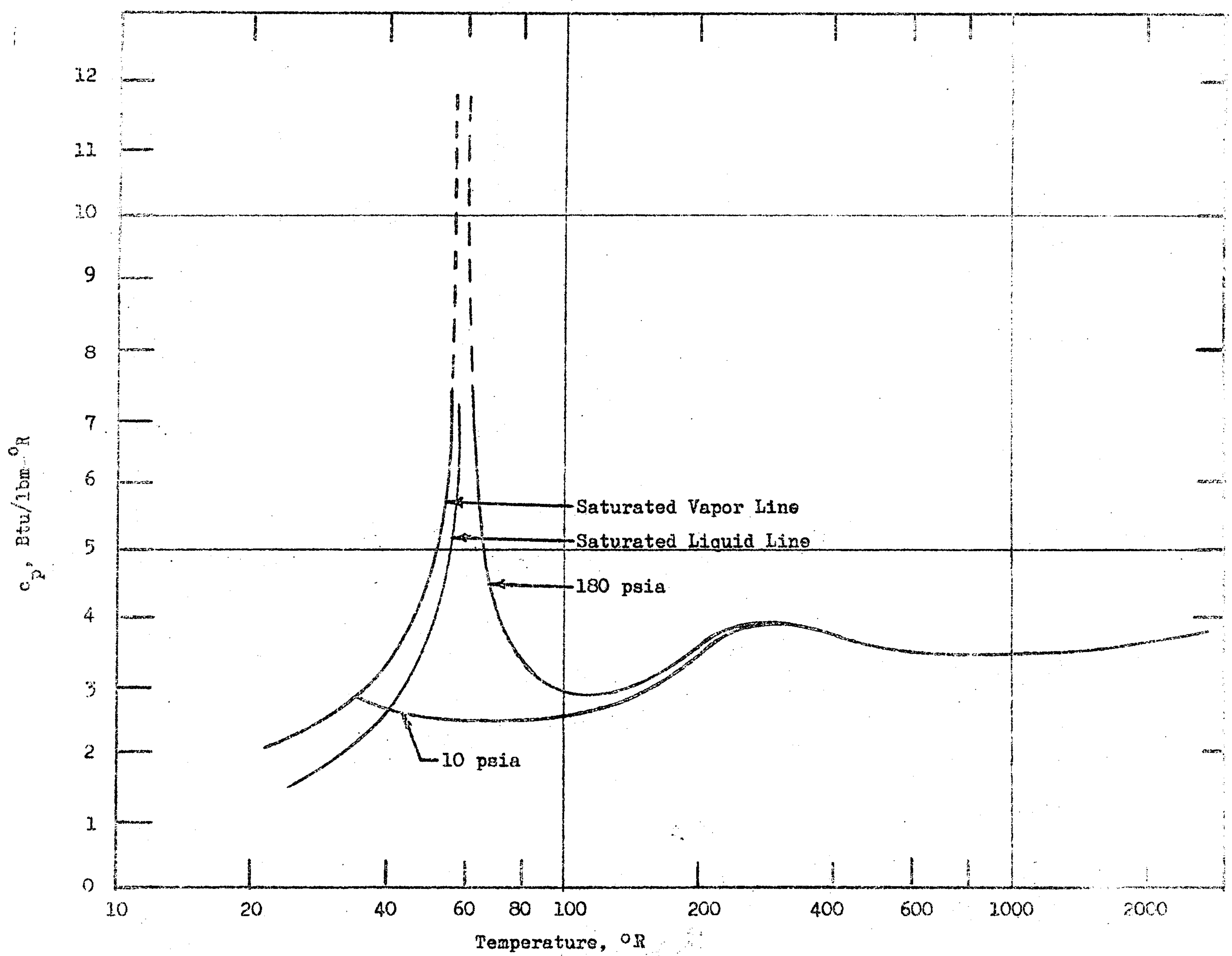

FIGURE 3 SPECIFIC HEAT AT CONSTANT PRESSURE OF PARA-HYDROGEN AS A FUNCTION OF TEMPERATURE AND PRESSURE